

NEW RESULTS ON $X(3872)$ FROM CDF

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In 2003 the $X(3872)$ particle was discovered by the Belle collaboration. Despite results collected since then, the nature of the state still remains unclear. In this contribution we report on new results on properties of the $X(3872)$ state using data collected with CDF II detector at the Fermilab Tevatron. The dipion mass spectrum and angular distributions are used to determine the J^{PC} quantum numbers of the state.

Keywords: $X(3872)$; charmonium; exotic mesons.

1. Introduction

The recent discovery of the $X(3872)$ state^{1,2} led to new interest in charmonium spectroscopy. It was found in a search for missing charmonium resonances. Despite enormous experimental and theoretical effort its exact nature is still unknown. Shortcomings of conventional explanations and the proximity of the $D^0 D^{*0}$ threshold have raised questions whether the $X(3872)$ could be an exotic form of matter, e.g. a mesonic molecule, $c\bar{c}g$ hybrid, etc.

Important for the understanding of the $X(3872)$ state are the quantum numbers spin J , parity P and charge conjugation parity C . Here we present a determination of these quantum numbers using $X(3872) \rightarrow J/\psi \pi \pi$ decays collected by the CDF II detector³. As quantities sensitive to the J^{PC} quantum numbers, the dipion invariant mass and the angular distributions are used. In both cases, the measured distributions are compared to the predictions for different J^{PC} hypothesis to infer the J^{PC} quantum numbers.

Details of the presented analysis can be found in Ref.^{4,5}.

2. Theoretical predictions

To obtain predictions for different J^{PC} combinations, we consider the $X(3872)$ decay as

a sequence of two-body decays. First, the $X(3872)$ decays to the J/ψ and $(\pi\pi)_{s,p}$ system, which is followed by decays $J/\psi \rightarrow \mu^+ \mu^-$ and $(\pi\pi)_{s,p} \rightarrow \pi^+ \pi^-$. In this view, the full decay amplitude is given by three amplitudes, one for each of the two-body decays and two "propagators", which connect vertices of the two-body decays. The amplitudes for the decay vertices are obtained using the helicity formalism.

The final amplitude for a given J^{PC} hypothesis is obtained from the squared total matrix element by averaging over all initial state helicities, incoherently summing over all final state helicities and coherently summing over intermediate state helicities.

The angular distributions are determined fully by the matrix elements for the vertices, which for the fixed helicities are given by the Wigner functions. In general more than one possibility to form spin J from the relative angular momentum L and spin S of the daughter particles exist. Of these independent amplitudes, only the ones with lowest L are used, as the higher L amplitudes are usually suppressed.

The "propagator" for the J/ψ is modelled by a δ function due to the very small width of the J/ψ . For the $(\pi\pi)$ system "propagator", the situation is more complicated as any description has some unknowns

inside, which doesn't allow one to make a precise prediction. For the $(\pi\pi)$ system in the S-wave we use multipole expansion⁶. The $(\pi\pi)$ system in P-wave is described by the intermediate ρ resonance for which we use a relativistic Breit-Wigner formula

$$\frac{d\Gamma_X}{dm_{\pi\pi}} = 2m_{\pi\pi} \frac{\Gamma_X(m_{\pi\pi}) \cdot 2m_\rho \Gamma_\rho(m_{\pi\pi})}{(m_{\pi\pi}^2 - m_\rho^2)^2 + m_\rho^2 \Gamma_\rho^2(m_{\pi\pi})}$$

In a case of broad resonances such as ρ the width in the Breit-Wigner formula has to be modified to

$$\Gamma_\rho = \Gamma_{0,\rho} \left(\frac{k^*}{k_0^*} \right)^{2L+1} \left(\frac{f(k^*)}{f(k_0^*)} \right)^2 \left(\frac{m}{m_0} \right)$$

due to the variation of the kinematic factor across the width. Here, k^* is the momentum of the decay product in the centre-of-mass system of the decaying particle and $f(k^*)$ is a form-factor. The model suggested by Blatt and Weisskopf is used in our analysis⁷. This model has one free parameter, which is the effective radius of the resonance for which typical values are in the range from 0.3 fm to 1 fm⁸. Another complication arises from possible ρ - ω interference, which is also included in our description.

3. Results

The first distribution, to which we look is dipion invariant mass distribution⁴. It is shown in Figure 1. The 3S_1 , 1P_1 and 3D_J multipole expansion for charmonia and $L = 0$ and $L = 1$ decay to the $J/\psi \rho$ were tested. Out of the tested models the 3S_1 multipole expansion and both $L = 0$ and $L = 1$ decay to the $J/\psi \rho$ are able to fit the data. While 3S_1 multipole expansion is able to describe data, it is disfavoured as this would be in tension with non-observation of the $X(3872)$ by the BES experiment⁹. Therefore only decays to $J/\psi \rho$ remain as a viable options for the $X(3872)$ decay. Unfortunately, at the current level of understanding, it is not possible to distinguish between $L = 0$ or $L = 1$ decays. The main reason is the uncertainty

in the modelling of the dipion mass shape. With reasonable parameters for the form-factors both can describe data. If we allow in addition ρ - ω mixing, for certain mixing phases, the $L = 1$ describes data even better than $L = 0$. This conclusion is in contradiction to the conclusion by Belle¹⁰. The origin of this disagreement stems from different modelling of the dipion mass distribution. The model used by the Belle collaboration doesn't include the form-factor in the Breit-Wigner formula. If we drop the form-factor from the description, the CDF dipion mass distribution is also inconsistent with the $L = 1$ decay to the $J/\psi \rho$. As it is not clear which model is the correct one and therefore, one should remain cautious at this stage.

In order to gain more information on the properties of the $X(3872)$ we now consider angular distributions⁵. The angles describing the decay are defined in Figure 2. Out of all angles, for unpolarised production, only three are sensitive to the J^{PC} quantum numbers. Those are $\theta_{J/\psi}$, $\theta_{\pi\pi}$ and $\Delta\Phi$. The last sensitive variable is the dipion invariant mass, but as we saw, there is considerable ambiguity in modelling. Therefore to avoid wrong conclusions, we fix the dipion mass distribution to an $L = 0$ ρ Breit-Wigner, which was found to describe data.

To extract angular distributions from

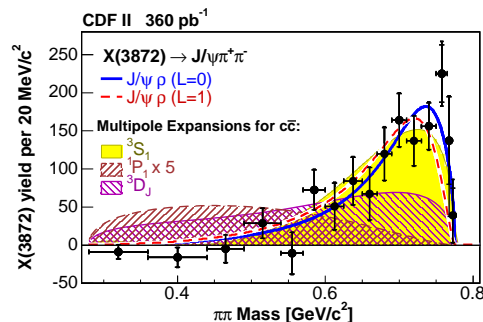


Fig. 1. Dipion invariant mass distribution with the predictions from multipole expansions and $L = 0$ and $L = 1$ decay to $J/\psi \rho$.

data, a slicing technique with a binned maximum likelihood fit is used, where the background is described by a second order polynomial and the signal by a Gaussian. The position and width of the Gaussian are fixed to the result of the fit to the full sample. In order to increase the discriminating power of the analysis, we exploit also correlations among the angles by usage of a 3-dimensional fit. We use $3 \times 2 \times 2$ binning, where three bins are used for $\Delta\Phi$ angle. The measured distributions are shown in Figure 3 together with the expectations for several J^{PC} hypotheses. To quantify the agreement between data and expectations, a χ^2 comparison is done. The resulting χ^2 values for different assignments are shown in Table 1. From the results we

conclude, that only the 1^{++} and 2^{-+} assignments are able to describe data, while all the others are excluded by more than 3σ .

Table 1. Result of the angular analysis for all tested assignments.

hypothesis	3D χ^2 / 11 d.o.f.	χ^2 prob.
1^{++}	13.2	27.8%
2^{-+}	13.6	25.8%
1^{--}	35.1	0.02%
2^{+-}	38.9	$5.5 \cdot 10^{-5}$
1^{+-}	39.8	$3.8 \cdot 10^{-5}$
2^{--}	39.8	$3.8 \cdot 10^{-5}$
3^{+-}	39.8	$3.8 \cdot 10^{-5}$
3^{--}	41.0	$2.4 \cdot 10^{-5}$
2^{++}	43.0	$1.1 \cdot 10^{-5}$
1^{-+}	45.4	$4.1 \cdot 10^{-6}$
0^{-+}	103.6	$3.5 \cdot 10^{-17}$
0^{+-}	129.2	$\leq 1 \cdot 10^{-20}$
0^{++}	163.1	$\leq 1 \cdot 10^{-20}$

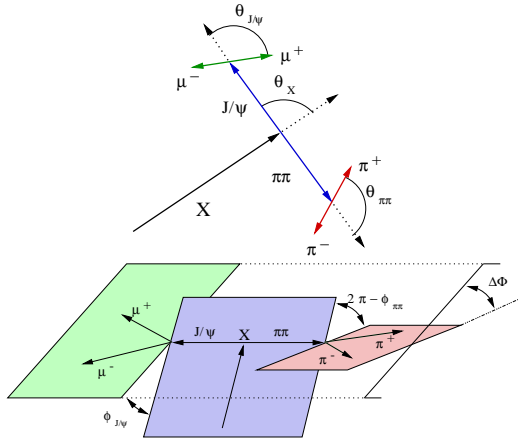


Fig. 2. Definition of the angles used in the angular analysis.

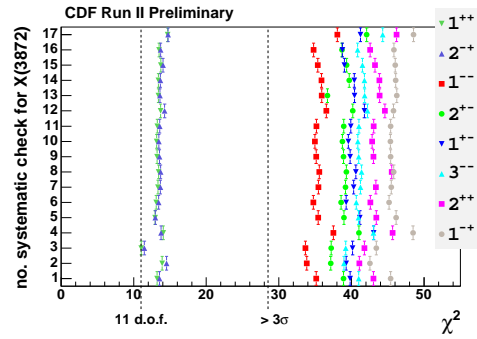


Fig. 4. Variation of the total χ^2 for different analysis variation. Vertical error bars are for visual guidance.

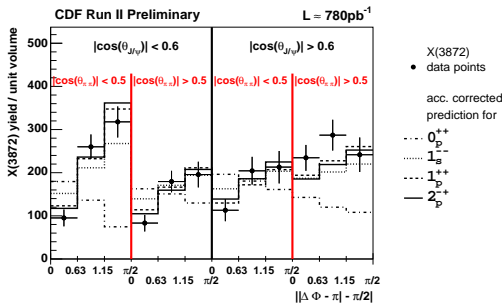


Fig. 3. Measured angular distributions (points) with expectations for several J^{PC} (lines).

To evaluate the stability of the result, we investigate several effects. The result of the investigation is shown in Figure 4, where the x-axis shows the resulting χ^2 , while the y-axis denotes the studied effect. The default analysis is shown as variation 1. We investigate the following variations: 2,3 variation in the fit window, 4,5 variation of the bin width, 6,7 variation of the Gaussian position, 8,9 variation of the Gaussian width, 10-12 variations in the dipion mass distribution,

13,14 variation of the p_T and η distribution of the $X(3872)$ and 15-17 variation of the details of acceptance correction. From Figure 4 we conclude, that none of the studied effects can alter the conclusion of the analysis.

4. Interpretation and Conclusions

After constraining the quantum numbers of the $X(3872)$ we come back to the question of the nature of $X(3872)$. The natural explanation is that the $X(3872)$ is a conventional charmonium state. In this picture the state with $J^{PC} = 1^{++}$ could be identified with χ'_{c1} and the $J^{PC} = 2^{-+}$ with the 1^1D_2 state. However in both cases there is some difficulty with the conventional explanation as the predicted masses¹¹ are different than the observed value. In addition the decay to $J/\psi \rho$ would violate isospin. But these arguments alone are not enough to rule out conventional charmonium.

The curious fact that the mass is close to the $D^0 \bar{D}^{*0}$ threshold gives raise to the speculations about exotic interpretation of the $X(3872)$. The most popular exotic interpretation is that it is $D^0 \bar{D}^{*0}$ molecule. The idea of the molecular interpretation dates back to mid seventies¹². Recently the models of a molecular state were developed by Tornqvist¹³ and Swanson¹⁴. For a molecular state they predict the quantum numbers $J^{PC} = 1^{++}$, which is compatible with the result of the analysis.

It should be added, that the recent observation of the $X(3872) \rightarrow D^0 \bar{D}^0 \pi^0$ by Belle¹⁵ prefers the 1^{++} assignment compared to the 2^{-+} .

To conclude we presented a determination of the J^{PC} quantum numbers of the $X(3872)$ state using dipion invariant mass distribution and angular analysis. We find, that only the assignments 1^{++} and 2^{-+} are able to describe data. All other tested assignments are excluded by more than 3 sigma.

While this result significantly constrains J^{PC} both the conventional charmonium explanation and the exotic one are still viable options. To distinguish them further studies both from experiment and theory side are needed.

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